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An integrated emotional and physiological assessment for VR-based active shooter incident experiments

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ABSTRACT

Unfortunately, active shooter incidents are on the rise in the United States. With the recent technological advancements, virtual reality (VR) experiments could serve as an effective method to prepare civilians and law enforcement personnel for such scenarios. However, for VR experiments to be effective for active shooter training and research, such experiments must be able to evoke emotional and physiological responses as live active shooter drills and events do. The objective of this study is thus to test the effectiveness of an active shooter VR experiment on emotional and physiological responses. Additionally, we consider different locomotion techniques (i.e., walk-in-place and controller) and explore their impact on users' sense of presence. The results suggest that the VR active shooter experiment in this study can induce emotional arousal and increase heart rate of the participants immersed in the virtual environment. Furthermore, compared to the controller, the walk-in-place technique resulted in a higher emotional arousal in terms of negative emotions and a stronger sense of presence. The study presents a foundation for future active shooter experiments as it supports the ecological validity using VR for active shooter incident related work for the purposes of training or research.

1. Introduction

The Federal Bureau of Investigation (FBI) defines active shooter(s) as: *"one or more individuals actively engaged in killing or attempting to kill people in a populated area"* [1]. The rate of occurrence of such incidents has dramatically increased over the past years, and these incidents affect a diverse group of people since they may occur in many different types of buildings, such as workplaces, schools, places of worship, shopping malls, and so on [2]. The average number of active shooter incidents in the U.S. between 2000 and 2009 was 8.6 annually. This number increased to 21.7 annually between 2010 and 2018 [3]. According to the FBI, in the U.S. in 2018, 27 active shooter incidents were reported in 16 states with 213 injuries and 85 people killed [1].

The tragic outcomes associated with these engagements typically encompass a brief timeframe. Seventy percent of active shooter incidents ended in less than 5 min, giving law enforcement personnel no time to intervene so forcing civilians to make life and death decisions [2]. For example, out of the 27 reported shootings in 2018, only 9 incidents ended with gunfire exchange between law enforcement and shooters [1]. In such incidents, the Department of Homeland Security recommends civilians follow three steps: run, hide, or as a last resort, fight back [4]. Usually, public safety and emergency preparedness personnel conduct drills to train people to follow these instructions and evacuate safely during such emergencies. However, the situational intensity perceived in active shooter incidents is difficult to replicate in evacuation drills and the lack of realism represents a major drawback for such methods, which may lead to inadequate evacuation behaviors [5]. Aside from training civilians, law enforcement agencies also rely on these drills to plan their response for active shooter incidents and train their personnel for such scenarios. The best practice in emergency management requires an evaluation, assessment and improvement cycle, which necessitates the repetition of these drills to improve the response plan for active shooter scenarios [6]. However, drills and associated exercises require significant time, staffing and financial resources and are not easily replicable, which is a crucial factor for an effective training of response teams [7]. Furthermore, the response plan is dependent on the emergency environment, and drills lack the ability to modify the environment easily (e.g., the response plan for a school, a mall or a hospital might significantly differ).

With the recent technological advancements, Virtual Reality (VR)

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techniques have provided a feasible alternative for evacuation drills. Virtual reality employs Virtual Environments (VEs) to replicate a real-life scenario [8]. Such replications could be made immersive by using Head Mounted Displays (HMD) [9]. VR is an efficient tool that has been increasingly used to simulate evacuation emergencies because it provides a safe, repeatable and controlled environment [10]. In addition, during a VR experiment, the threat of a building emergency—regardless of its nature—is realistic enough that people can perceive it and react to it in a similar way to a real emergency [11]. Data from VR experiments are crucial for understanding how people react in such incidents, for example helping others [12], herding [13] and how different building attributes may affect the evacuation in these scenarios: elevators [14], corridors [15], signage [16], exit locations [17] and architectural visibility [18].

An important factor that verifies the effectiveness of VR studies for active shooter experiments is the concept of presence. Presence is usually used to describe the human experience in VR and is simply defined as the subject's feeling of "being there" [19]. Lombard and Ditton [20] argued that a high level of presence can be achieved when the subject loses awareness of the technology being used and the real environment. On the other hand, Slater [21] postulated that "identifying the VE as a place the subject visited rather than a set of images" is the key aspect of presence. Despite the large number of definitions, the concept of presence and its effect on the human experience in VR is still considered a rather complex notion [22]. That being said, only those persons experiencing a strong sense of presence in VEs would feel, think and behave in the virtual experiment as they would in a comparable real life situation [23]. In fact, Riva et al. [24] indicated that the sense of presence is magnified in the "emotional" VEs and participants' emotional states are directly affected by the level of presence.

One of the crucial components of VR applications is the locomotion technique, which enables the participant to navigate in the VE. The choice of locomotion technique is dependent on the experimental scenario under study. In the case of an active shooter VR experiment, navigation through the VE is an essential component (e.g., to explore, run, hide, fight), especially in evacuation studies where researchers aim to understand how participants move to evade the threat. A wide variety of locomotion techniques for VR experiments exist: some are more natural (real walking, walk-in-place) while others are more artificial (controller/joystick, teleportation) [25]. Several studies have investigated the technical and practical attributes of the different VR locomotion techniques without emphasizing the effect of the VR locomotion on the human experiences when conducting VR-based experiments [25,26]. This locomotion experience is mostly defined by the sense of presence [27], and the selection of the appropriate locomotion technique in VR has been proven to have a direct effect on presence [28].

Developed on this background, this study aims to assess the potential of using VR as an experimental tool for active shooting emergency incidents. The proposed research work explores two main objectives: (1) to measure the sense of presence of human subjects who are immersed in an active shooting scenario via a VE using physiological data and an emotional response–based approach and (2) to compare between two VR modalities: a walk-in-place treadmill and a controller with the aim of investigating which modality provides the human subjects a more realistic experience and enhances their sense of presence.

2. Literature review

2.1. Emotional and physiological measures of presence

A common measure of the effectiveness and ecological validity of any VR experiment is the sense of presence that subjects witness in the corresponding VE [29]. When researchers use VR as a predictive method for human behavior, they aim to maximize the ecological validity of their experiments [30]. The best way to assess the ecological validity of VR-based experiments is to compare its results and conclusions to similar real-life scenarios [31]. However, this comparison is difficult to make, if not impossible, for the case of active shooter incidents, as it poses safety risks and ethical concerns. The lack of a comprehensive mechanism for the assessment of the ecological validity of VR experiments has made them prone to severe criticisms.

To overcome this problem, researchers explore the concept of 'sense of presence' to defend the ecological validity of their VR-based experiments [32]. When placed in a VR environment, people are conscious that the environment itself and the occurring events are artificial. However, when the barrier between what is real and what is artificial start to collapse, the interaction with the VE and participants' responses to the VR's events become more reliable [22]. Physiological measurements attempt to investigate the sense of presence in VR by capturing changes in heart rate, respiration, skin temperature and conductance, EEG waves, etc. to identify the intensity and type of reaction participants exhibit [33].

Yu et al. [34] suggested that the sense of presence in VR can be described as the degree to which participants react realistically to events in the VE. Such realistic reactions are not only specified by the physical actions or discrete decisions taken by the participants, but also by the emotional response they experience due to the events they witnessed in the environment. Riva et al. [24] showed that there exists a circular relationship between the feeling of presence in VEs and the induced emotions: the sense of presence increases in emotional environments and participants' emotional valence and arousal is highly influenced by their sense of presence in VEs. Finally, Diemer et al. [35] argued that VR researchers interested in the emotional experiences and emotional behavior (fear, stress, anger) should make sure their environments are able to induce reliable emotional reactions to enhance the sense of presence and realism of the VE

Active shooter-based VR experiments should reproduce a high stress level and emotional response to be considered successful, thus allowing researchers to better understand the decision-making process of people during such events. Lerner et al. [35] postulated that emotions form a major driver for human behavior and decision-making and Cheng et al. [36] found that people experiencing the emotions of stress, fear and anxiety may make impaired decisions. In fact, Seo and Barret [37] postulated that insight about the people's emotional response could explain how people react during stressful events. Cohen et al. [38] claimed that the analysis for emotions when studying stressful situations in VR is at the core of understanding human behavior and decision-making under stress. For instance, the accumulation of negative emotional responses under stress drains the cognitive functions that can be used to shape better decisions [39].

Thus, several studies have examined the emotional response of people under various stressful emergencies in VR. For instance, during health crises, non-professional employees in hospitals are easily affected by stress, which degrades their decision-making and performance thus reducing the treatment quality. De Leo et al. [40] proposed a VR environment to train non-professional medical health operators in case of a health emergency due to a natural disaster, or a catastrophic event, etc. and to understand their psychological response and its effect on their performance. In another example, Chittaro et al. [41] studied the level of fear of people when placed in a VR experiment of aircraft emergency water landing. Other works attempted to investigate the feasibility of studying human behavior during terrorist attacks in VR by studying participants' threat appraisal and the corresponding emotional response [42]. Thus, there is a need for studies that focus on people's emotional responses in assessing the feasibility of using VR for active shooter experiments. This type of experiment will require subjects to think, decide and act as if they were in a life-threatening event, and present vital information to understand how people react in light of such situations and what measures can be taken to counter active shooter incidents. Therefore, for an active shooter VR experiment to be effective and yield relevant findings, participants must exhibit emotional responses that are like what an actual incident is predicted to induce, even if at a reduced level.

Emotional response of subjects interacting with VEs has been measured in prior work with a clear correlation found between the sense of presence of subjects and their emotions [43]. There are numerous emotional models that assess human emotions such as the Ortony, Clore, and Collins (OCC) model [44], or the basic emotions sets [45], however, emotional responses are best defined by two measures: valence and arousal. Valence is a term used to describe a positive or negative affectivity, whereas arousal is a term used to measure how calming or exciting the information is [46]. Both valence and arousal may be easily quantified by using subjective self-reports, such as the Positive and Negative Affect Schedule (PANAS) [47]. With PANAS, participants rate the extent to which they felt 20 emotions, with 10 items measuring the positive effect (such as joy, cheerfulness or happiness) and 10 items measuring the negative effect (such as anger, fear or anxiety), on a 5-point Likert scale that ranges from *very slightly* to *very much*. A major disadvantage for such a tool is the subjectivity of participants; thus, the rated emotions may not be accurate. A solution for this would be to record physiological data which present an objective measure of participants' emotions.

Several studies proved that emotional arousal can be associated with certain types of physiological measurements. For instance, Nasoz et al. [48] suggested a way to link physiological signals from wireless sensors with emotions. Electroencephalography (EEG) is one method that has been used to evaluate participants' emotions in VR experiments [49,50]. Yet, EEG devices are expensive [51] and EEG data are usually noisy and require experts to interpret [52]. Functional magnetic resonance imaging (fMRI) represents another method to evaluate the brain functions using X-rays radiation and positron emission tomography [53]. This method has been recently employed to identify the emotions witnessed by participants in VR experiments [54]. However, fMRI is very expensive, and requires that the participant stays still while being scanned, which is not convenient with VR experiments using non desktop-based experiments [55]. Furthermore, fMRI uses high strength magnetic fields, which would preclude most electronics, including the VR headsets [55]. Skin conductance has also been used to identify arousal in participants' responses to emotionally charged VEs [56]. However, skin conductance shows high levels of noise when subjects are required to move during the experiment [57]. Similar to skin conductance, skin temperature can also be an indicator of the human emotional state but also presents inaccuracies if the subject is moving [58]. Endocrinal measures have been also associated with emotions identification. However, such measures require medical tests (e.g., cortisol blood tests or thyroid gland tests, etc.) which entails extensive medical expertise [59]. Other studies investigated the feasibility of using facial expressions to determine the emotional response participants show during a VR experiment [60]. However, these methods fall short when it comes to VR experiments using HMD, because of the partial facial occlusions it imposes [61].

Heart rate is another predictor of the emotional state and frequently used in assessing emotions in VR [62,63,64]. Active shooter events are predicted to increase the anxiety, fear and stress levels of those who witness them. These emotions have been associated with increased blood pressure, respiration and heart rates, which justifies why numerous VR studies focusing on stressful events have relied on heart rate measurements in their assessment of the subjects' responses to the VE events [65,66]. Also, heart rate sensors are inexpensive and easy to use. Furthermore, the corresponding data can be easily interpreted, and present low noise levels with movement which makes it suitable for VR experiments that requires intensive body activity like the case of active shooter experiments [67].

To summarize, various objective approaches have been used in the literature for assessing emotional valence or arousal, and researchers have combined both subjective and objective measures for a more comprehensive approach. It is believed that the integration of both can efficiently distinguish between positive and negative emotions and can precisely depict the perceptive variations in the magnitude of emotional responses [68]. This framework has been proven by the work of Zou et al. [66] who used an integrated approach to assess the emotional responses of participants in a VR fire evacuation scenario. Their results suggest that such a method is feasible to assess the sense of presence of the participants and the ecological validity of this type of VR experiment. Furthermore, the proposed approach was able to distinguish between various emotions when participants were immersed in different levels of realism.

2.2. Locomotion technique and presence

The navigation mode adapted for participants' movements in a VE is an important factor that affects the sense of presence and as such the ecological validity of any VR experiment [69]. VR locomotion is the technology used in VEs that allows movement from one place to another. Different methods have been employed to enable movement in VEs. Boletsis [70] identified several documented locomotion techniques for VR. In their review of 36 studies, Boletsis found that the most widely used navigation methods were: real-walking, controller and walking-in-place. More recently, Boletsis and Cedergren [25] recharacterized VR locomotion into four different types: (1) motion-based also known as semi natural which supports some kind of continuous physical movement through treadmills for instance [71], (2) room-scale based which enables continuous and natural real- walking in the real environment that is replicated in the VR [72], (3) controller-based which employs artificial continuous movement through controllers in the VR [73] and finally (4) teleportation-based which uses discontinuous artificial movement in the VR such as "jumping" [74]. The real walking is considered a part of the room-scale type, and the walk-in-place falls into the semi natural VR locomotion. Controllers mechanisms are separated into the continuous controller movement or they can support a discontinuous movement such a flying, jumping or other types of teleportation.

The real-walking locomotion technique allows a participant to move freely within a limited physical space. VR experience with real-walking is superior to any other type of locomotion technique because of its simplicity and realism, however real-walking becomes problematic when the VE is larger than the physical space in which the experiment takes place [75]. In the controller method—also called artificial locomotion, the participant directs his movement in the VE through a joystick. Although it is easy to use, a major deficiency in this method is that it can cause motion sickness. The participant, whether standing or sitting, witnesses a discrepancy between his/her vision and the movement related systems in the body [76]. Finally, walking-in-place is a navigation mechanism that falls in between real-walking and controller locomotion techniques. This method allows participants to physically engage their body in a realistic walking motion without moving forward [77]. In other words, the participant can walk in the VE by mimicking movement without physically changing the body position. Researchers usually rely on walk-in-place and controller-based method in their studies because the real-walking method requires spacious physical space to navigate large VEs [78]. On the other hand, the teleportation-based methods employ discontinuous movement which becomes a major concern when participants' experience is of high importance [79].

Findings show that continuous movement is associated with enhanced sense of presence when compared to discontinuous movement such as during a teleportation-based VR experiment [80]. However, the comparison between locomotion techniques with similar continuous movement patterns becomes harder when it comes to assessing their effect on presence. The literature presents a discrepancy in reported results about the effect of real-walking, treadmill, and controller techniques on participants' sense of presence. While some found real-walking to be the most efficient walking modality for enhanced presence experience [81], others failed to find a significant difference in the presence level, between a controller-based movement and a walk-in-place locomotion technique [82]. However, most of these studies use simple VEs, which renders such comparisons not sufficiently representative. Furthermore, the common approach of addressing presence, using solely subjective surveys could be the reason behind the discrepancy in results.

3. Methodology

This study employs a systematic framework, in which it bases the sense of presence on the emotional response of the participant in a complex and stress-inducing VR active shooter experiment using both subjective responses and objective data. The framework is also used to determine which locomotion technique; walk-in-place or controller, increases the participant's sense of presence. Three main hypotheses are tested: regardless of the locomotion technique, an active shooter experiment in VR is associated with an increase in negative emotions, and decrease in positive emotions **(H1)** as well as a rise in heart rate **(H2)**, and finally, walk-in-place locomotion technique is associated with enhanced sense of presence compared to the controller-based locomotion technique **(H3)**. The following subsections present the methodology adopted in this work.

3.1. Virtual built environment

According to the FBI, between 2000 and 2018, 42 of the 277 active shooter incidents in the U.S. were engaged in school environments (which is the second highest number of occurrences in buildings following places of commerce). Fifty-seven percent of those incidents occurred in a high school [3]. Thus, we have designated the virtual emergency scenario to take place on the ground floor of a virtual high school building. Fig. 1 shows the plan view of the floor. The floor plan includes a main entrance that leads to a lounge; to the left of the lounge there is a reception area, and on the right, there is Hallway 1 which leads to the second exit of the building (assuming the entrance can also be considered as Exit 1). To the north of the lounge; Hallway 2 leads to Exit 3 on the right and the cafeteria is situated on the left. The cafeteria is divided into two parts: the dining area and the back kitchen to the north of it. The kitchen allows participants to leave the building through Exit 5. Hallway 3 located to the north of Hallway 2 and to the right of the cafeteria, goes all the way to Exit 7. There exist 4 classrooms and 1 exit (Exit 4 to the south and 6 to the north) on each side of this hallway.

The school building, including its basic structure (e.g., walls, floors, doors, and windows) and furniture (e.g., tables and chairs) were first modelled in Revit 2019®. The Revit model was then exported in IFC format and imported to Unity game engine using the PiXYZ plugin for Unity®. In Unity, more objects (e.g., plates on dining tables), the outdoor environment, as well as lighting, texture, and materials were added to make the VE more photo realistic (see Fig. 2).

Interactions between the participants and the built environment (e.g., opening doors) were also programmed in Unity. For example, when the participant gets close to a door (<0.5 m), the door opened automatically. Moreover, non-player characters (NPCs) [83] were incorporated in Unity to represent building occupants and the shooter. A total of 82 NPCs (81 building occupants and 1 shooter) were included in the VE. The number was determined based on the tradeoffs between the level of realism and performance of graphics card. Among the 81 occupants, 25 were initially in the cafeteria, 3 were in the lounge, 3 were in Hallway 2, and 6 were in Hallway 3. In addition, there were 4 NPCs in the teacher's lounge and 4 in the outdoor dining area (i.e., outside Exit 3) at the beginning. The rest of NPCs were placed in the classrooms on both sides of the Hallway 3. These NPCs were based on body scanning of real people, to make them look more realistic. Furthermore, to simulate the shooting incident, the particle system in Unity was used to visualize the flash from the firearm when the shooter was shooting, and the Ray-casting technique in Unity was used to enable the shooter to find visible targets (i.e., building occupants). To make the VE a more realistic one, audio files replicating the sounds of what people would hear in a cafeteria were added.

3.2. Virtual active shooter scenario

The experiment was conducted in a first-person perspective (see Fig. 3) i.e., the graphical perspective of the experiment rendered from the viewpoint of the participant. This plays an important role in giving the participant an immersive VR experience [84]. The VE experiment

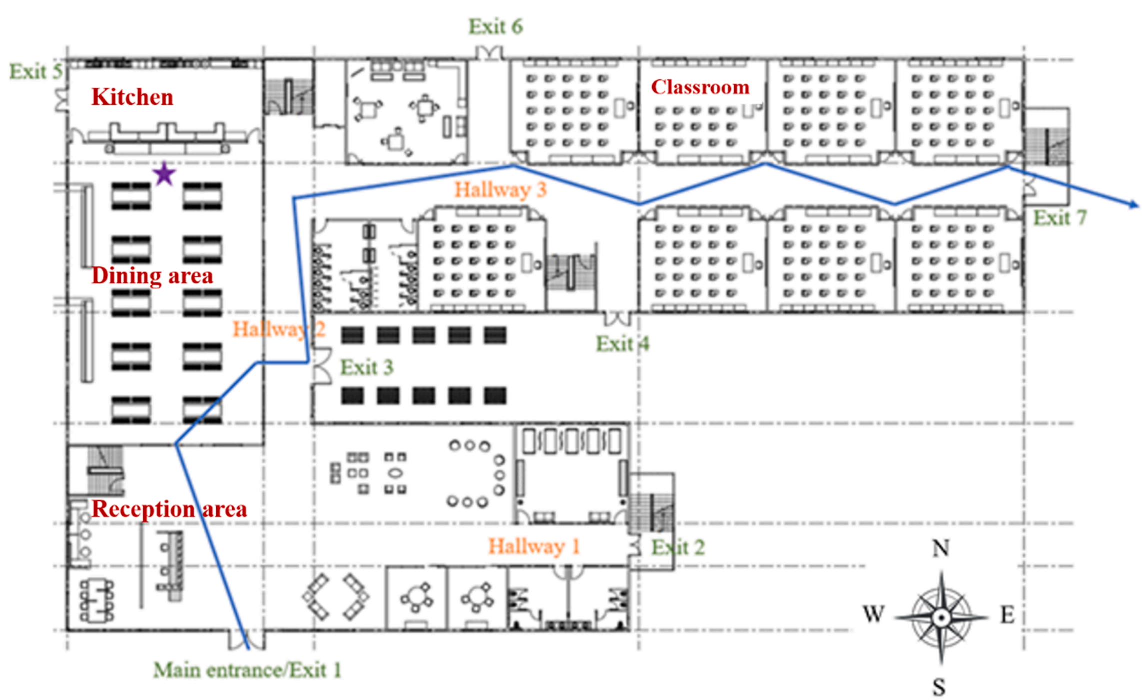

Fig. 1. Floor plan of the VE (blue line represents the trajectory of the shooter and the purple star represents the initial point for each participant). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

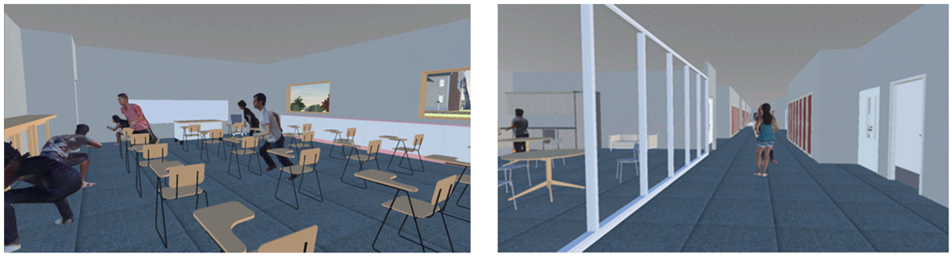

Fig. 2. A classroom (right); Hallway3 (left).

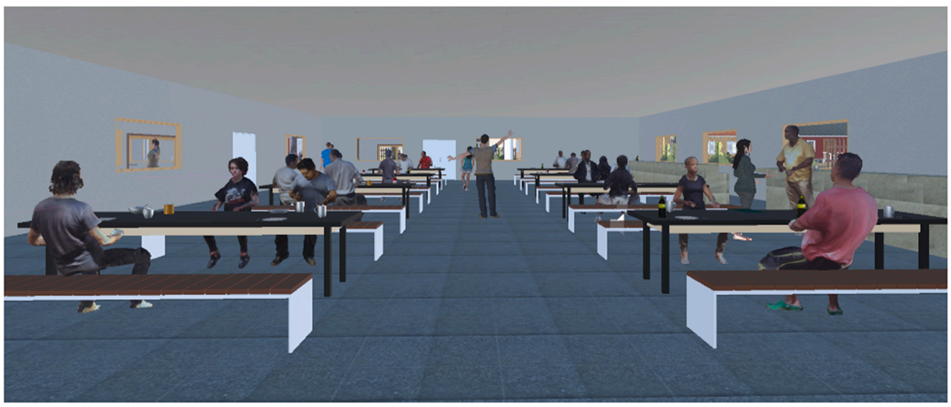

Fig. 3. Virtual environment as seen from the participant's initial viewpoint.

begins at the dining area of the cafeteria with NPCs eating and holding conversations (see Fig. 1, the star represents the initial position for the participant). Some NPCs were seated while others were walking or talking on the phone (Fig. 3).

According to the FBI, among 42 active shooter incidents occurring in schools in the U.S. between 2000 and 2018, all involved single shooters and most of them (96%) were males [3]. Therefore, the shooting scenario was performed virtually by a single male NPC; the shooter was programmed as a teenager, because in the majority of school shooting incidents the shooter was a student at the school (56% between 2000 and 2013) [3]. In the active shooter scenario, the shooter enters from the building's main entrance and starts shooting people. The trajectory of the shooter is shown with a blue line in Fig. 1. Whenever the shooter faces an NPC, the shooter would shoot the NPC. Due to ethical considerations, no pain was induced nor was blood visible during the VR experiment. The shooter was equipped with a semi-automated AK-47 assault rifle, accompanied by appropriate shooting sound effects in the background to facilitate a more realistic experience. A former FBI agent and weapons expert approved the sound and frequency of the shooting audio effects. At the moment of the shooting, a crowd panic audio was played and NPCs in the cafeteria either hid or moved toward predefined destinations. The experiment ended when the shooter exits the building through Exit 7, and the participant is then asked to remove the headset. The overall duration of the experiment was around 2 min.

3.3. Locomotion techniques

In this study, two locomotion techniques were compared: walk-in-place treadmill and controller. The real-walking modality was left out because of the restrictions on the physical space. Both modalities utilized an HTC Vive pro eye system [85], and the system included a head-mounted-display (HMD) for visualizing the immersive VE, two base stations for positioning the HMD and controller, and a noise cancelling headphone connected to the HMD to provide sound effects. In both locomotion conditions, participants were able to change their body orientations by changing their head orientation in the physical world.

The only difference between the two modalities lies in the motion mechanism itself. For the walk-in-place condition, a Virtuix Omni [86] was used. The Omni is a locomotion simulator, designed to allow participants to walk within the VE. As shown in Fig. 4, the treadmill has a bowl-shaped surface that requires the participant to wear low friction shoes for movement. The simulator can track the participant's position, speed and length of his/her stride during the experiment by inertial sensors. The treadmill has a harness, which was placed around the waist, enabling the tracking of body orientation, completely separate from the leg movement. The data was transmitted to a computer, which translates it to movements in the VR environment. For the controller condition, participants were provided a controller to move around the VE while standing in the same position (Fig. 4). The participants look into the direction they want to walk in and press a button on the controller to move.

3.4. Study sample

Eighty participants voluntarily completed the experiment, of which 28 were females and 52 were males. The participants had a mean age of 25.6 with a standard deviation of 5.1. The participants were mainly graduate and undergraduate students who completed a written informed consent form before conducting the experiment. The study was approved by the Institutional Review Board (IRB).

3.5. Experimental procedure

Participants were randomly assigned to one of the two conditions: forty participants completed the experiment using the walk-in-place technique and forty participants completed the experiment using the controller-based technique. Before conducting the experiment, participants were asked to fill out a survey that asked them about their gender, age, and whether they had previous experience with VR. Health related information was also collected to determine if a participant is eligible to participate in the experiment. The participants were asked to wear a Vernier heart rate monitor around their chest, under their clothes. The

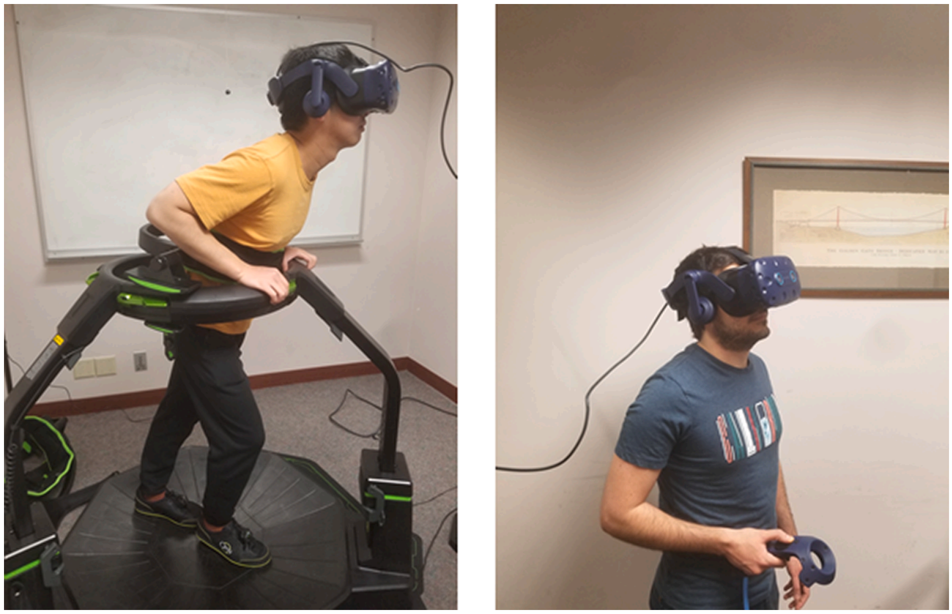

Fig. 4. Locomotion techniques: walk-in-place (left); controller (right).

chest strap allows for data to be wirelessly transmitted to a Vernier interface "Graphical Analysis™ 4" installed on a nearby computer [87]. Participants were required to complete a training session to familiarize themselves with the movement using their associated locomotion technique. During the treadmill training session, participants were asked to walk for two minutes, followed by another two minutes of running. This was done with the aim of creating a benchmark for the heart rate data. The participants were also able to crouch in the VE by crouching in the real world; when the participants bent their knees and lowered their upper torso, they experienced a similar body action in the VE. During the training session for the controller condition, participants were explained how to move in the VE using the controller. Participants heart rate was also recorded during the controller training session as a benchmark. The movement speed for this modality was fixed at 2.5 m/s. The speed was determined based on pilot trials and was set to simulate running movement in the VE without causing any sickness or dizziness to the participants. If the participants were standing, to change their direction of movement they had to rotate their body to the intended direction while maintaining the same position.

After the training session, the participants in both groups were asked to complete a second survey, asking them about their emotional states using the PANAS scale and the physical symptoms they are experiencing (such as dizziness, nausea, stomach awareness, vertigo). The survey used a 5-point scale with 1 representing not at all and 5 being extremely. The survey required about 7–10 min to complete, which was considered as the resting period for the participants to restore the original heart rate before going into the experiment session to ensure the training session's elevated heart rate did not influence participants' heart rate in the active shooter experiment. Baseline related data were collected after the training session to ensure that any excitement or frustration due to the locomotion technique itself was captured and as such the difference in emotions was due to the active shooter experiment (not due to the stress of trying to get familiar with VR tools or excitedness due to experiencing new tools). There might be some indirect effects on the baseline of emotions, but that effect was captured through the PANAS baseline after training, and as such would not affect the results, since the difference in emotions could be attributed to the active shooter experiment itself. Before conducting the experiment, the participants were told that they would experience an emergency in a building, and they were asked to react as they would in a real-life scenario. No explicit explanation was provided with regards to the type of in-building emergency scenario. Then, the experiment commenced.

After the experiment, subjects were asked to complete the final survey that asked them again about their emotional states using the PANAS scale and the physical symptoms they are witnessing. The survey also asked 27 unique questions that were based on the six major classes presented in the Igroup Presence Questionnaire (IGP) [88]. These 6 classes are: spatial presence, quality of immersion, interface awareness, realism, exploration of the VE and predictability. The spatial presence is defined as the sense of "being in the VE", the quality of immersion relates to sensory factors (audio-visual effects), the interface awareness describes how natural and realistic interface devices are associated with bad interaction with the VE, the realism investigates how comparable to reality is the VR experience, the exploration of the VE looks into how easy it was for the participant to modify their viewpoint, and predictability studies the degree participants were able to anticipate the consequences of their interactions with the VE. Participants responded to the questions using a 7-point scale from 1 (*Not at all*) to 7 (*Extremely/ Completely*).

4. Results

4.1. Emotional response analysis (PANAS)

The assessment of the emotional response is conducted through the PANAS emotional scale. For every participant, an average score of all the positive and negative emotions was calculated before and after conducting the experiment. We conducted a 2 (valence) × 2 (time) × 2 (locomotion technique) factorial ANOVA with valence (positive and negative) and time (before and after) as the within-subjects effect, and locomotion technique (walk-in-place and controller-based) as the between-subjects effect. As predicted (H1), there was a significant interaction between time and valence ($F(1,78) = 110.29$, $p < 0.001$) across locomotion techniques, negative emotions increased after the participants experienced the active shooter experiment and, likewise, positive emotions decreased. Fig. 5 presents the mean scores for the positive and negative emotions before and after conducting the experiment, along with the associated standard errors, irrespective of the locomotion technique.

Although unexpected, there was a significant three-way interaction between valence, time and locomotion technique ($F(1, 78) = 4.70$, $p = 0.03$). By examining the means in Fig. 6, we see that both locomotion

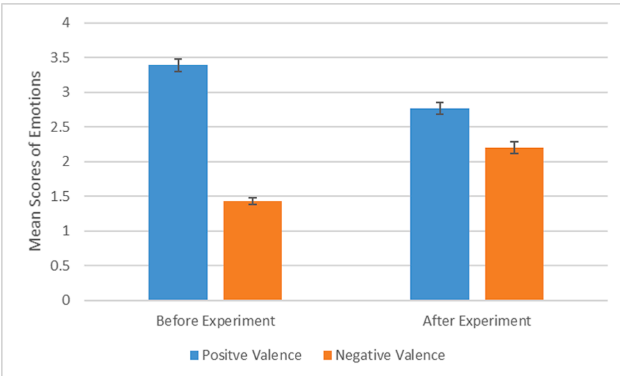

Fig. 5. Mean values of emotions before and after conducting the experiment.

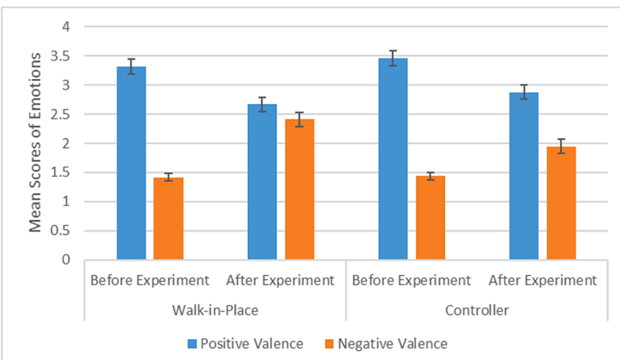

Fig. 6. Mean values of emotions, for the two locomotion techniques, before and after conducting the experiment.

techniques reduced the positive emotions to the same extent, but the walk-in-place locomotion technique increased negative emotions more than the controller locomotion technique. After conducting the active shooter VR experiment, participants who used the walk-in-place technique appeared to become more aroused in terms of negative emotions than those who used the controller.

Although less relevant to our research hypotheses, other effects also emerged. There was a significant main effect of valence ($F(1,78) = 199.70$, $p < 0.001$), such that -across both time points- people reported more positive emotion ($M = 3.08$) than negative emotion ($M = 1.80$). There were also two significant two-way interactions with the locomotion technique (valence by locomotion technique $F(1, 78) = 4.73$, $p = 0.03$; and time by locomotion technique $F(1, 78) = 5.43$, $p = 0.02$); however, these effects were qualified by the significant three-way interaction described above. The main effect of time (across valence and locomotion technique) on emotions did not reach significance ($F(1, 78) = 2.23$, $p = 0.14$).

4.2. Heart rate analysis

To determine the effect of the VR-based active shooter experiment on the heart rate of the participants, the average heart rate during the training session and during the experiment was calculated. The heart rate signals of 5 participants were dropped from the analysis (1 from the walk-in-place condition and 4 from the controller condition), due to technical difficulties. The analysis was done as a 2 (time) × 2 (locomotion technique) factorial ANOVA with time (during the training session and during the experiment session) as within-subjects effects, and locomotion technique (walk-in-place and controller-based) as a between-subjects effect. Irrespective of the locomotion technique, the results present a statistical significance in the heart rate averages over time ($F(1,73) = 18.976$, $p < 0.001$). The mean average heart rate during the training sessions was 99.84 Beats Per Minute (BPM) and 105 BPM during the experiment.

However, there was no statistically significant interaction between time and the locomotion technique ($F(1,73) = 18.976$, $p < 0.001$), which means that there is not enough evidence to assume that a certain locomotion technique can induce more heart rate stimulus when a participant completes an active shooter VR experiment. Fig. 7 presents the mean values of the heart rate data for the walk-in-place and controller-based locomotion techniques during the training and experiment sessions.[1]

4.3. Presence and user experience

As mentioned earlier in the methodology section, the participants were asked to answer questions related to the degree of realism of their experience, immersion, environment's responsiveness, their sense of engagement, and how realistic their response was towards the active shooter incident. These questions were grouped according to the six major classes presented in the IGP questionnaire: spatial presence, quality of immersion, interface awareness, realism, exploration of the VE and predictability. An average score was calculated for each class per participant. It is worth noting that all questions were designed in a way that a higher score represents a positive implication. The analysis was performed in two parts as explained below.

The first part of the analysis is comprised of a single mean *t*-test to compare the participants mean scores per class (regardless of the locomotion technique) with a hypothesized mean of 4 (average vote on the scale). For this test, the interface awareness class was dropped off the analysis because it is more related to the locomotion technique used. The purpose of this test was to detect whether the classes under study enhanced the user experience in the VR experiment. Table 1 presents for

Fig. 7. Mean values of the heart rate data during the training and experiment sessions (for both locomotion techniques).

-Analysis with regards to the motion sickness in both locomotion techniques was completed. An average score per participant was calculated for all these symptoms. An independent sample
t-test was completed, and the results showed no statistical difference between the different two locomotion techniques ($t(79) = 0.925$, $p = 0.358$).-Further analysis with regards to the effect of gender on emotional response was completed. The results showed no statistical difference between male and female participants in their emotional response, nor any interactions with other factors such as time or valence. Also, gender had no statistically significant effect on the heart rate response to the virtual experiment.-The statistical effect of "previous experience with VR" on the emotional and physiological responses through PANAS and heart rate analyses was not studied because those without previous experience (66 participants) greatly outnumbered those with previous experience (14 participants).

Table 1
Descriptive Statistics and single mean *t*-test results describing the user experience.

Class	Overall Mean	t value	p value
Spatial Presence	5.00 ± 1.18	15.02	7.2×10^{-25}
Quality of Immersion	5.38 ± 0.86	24.68	7.1×10^{-39}
Realism	4.63 ± 1.09	13.29	7.6×10^{-22}
Exploration of VE	5.09 ± 1.45	13.01	2.4×10^{-21}
Predictability	4.9 ± 1.13	15.39	1.7×10^{-25}

each class the overall mean, standard deviation, t-value of the single mean *t*-test and the associated p value.

The second part of the analysis is comprised of an independent sample *t*-test to identify which locomotion technique had higher effect on the following classes: spatial presence, interface awareness, realism, exploration of VE and predictability. The quality of immersion class was removed from this analysis because the audio-visual effects incorporated in the experiment were not affected by the locomotion technique adopted. Table 2 presents the average scores for both locomotion techniques along with their standard deviations. The table also shows the t-value of the statistical test and the associated p value.

Results in Table 1 show that the means for all subscales were statistically significantly higher than the hypothetical mean of 4 ($p < 0.001$). This finding demonstrates that participants showed a high sense of presence in the VE, they felt immersed, their experience was realistic enough, they were able to explore the VE smoothly and their interactions with the environment were predictable and realistic. The quality of immersion showed the highest overall mean ($M = 5.38$) in comparison to the remaining categories, while realism category scored the lowest overall mean ($M = 4.63$). On the other hand, results from Table 2 suggest that there exists a statistical significance between the two locomotion techniques when it comes to spatial presence ($t(79) = 2.31$, $p = 0.02$) and interface awareness ($t(79) = 2.08$, $p = 0.04$). The mean values of spatial presence and interface awareness were higher in the walk-in-place locomotion technique ($M = 5.30$, $M = 4.70$ respectively) than those of the controller-based locomotion technique ($M = 4.70$, $M = 4.22$ respectively). There was no statistical significance between the two locomotion techniques in terms of realism, exploration of VE and predictability.

5. Discussion

During active shooter incidents, anxiety, stress and negative emotions may overwhelm people and can affect their decision-making and behaviors. An effective active shooter incident experiment should be able to replicate the stressors and emotions people witness in a real-life scenario. This emotional replication increases the reliability of findings related to human behavior and evacuation analysis for active shooter VR-based experiments. Previous research studies investigated the emotional response of participants when exposed to emergencies in VR-based experiments (e.g., fire, earthquake). However, the present work is unique as it investigates the emotional and physiological response of participants involved in an active shooter scenario. The approach included a subjective evaluation of emotional response through the PANAS emotion scale and an objective assessment of the physiological response by heart rate analysis. Furthermore, both the sense of presence and the user experience were studied using subjective evaluations.

In general, the results show that participants started with a low overall level of negative emotions and a high level of positive emotions. After completing the experiment, there was a marked decrease in the overall level of positive emotions and a rise in the overall level of negative emotions. Unlike the results presented by [62] which focused on VR-based experiments for fire incidents, the statistical analysis of the emotional response using PANAS was significant in the present study. One reason behind this discrepancy might be that the active shooter experiment induces more stress and anxiety in comparison to fire emergency VR-based experiments.

Heart rate variation (bpm) was used as an indicator of the physiological response in this study. The results revealed that participants showed an increase in heart rate when going through the experiment, irrespective of the locomotion technique they were assigned to. This finding further shows that the active shooter experiment was stressful enough for the participants' heart rate to increase. The results are in accordance with studies conducted on subjects in fire and earthquake VR-based emergencies [66,89] where the analysis showed statistical significance in the heart rate increase.

Taken together, the emotional and physiological responses witnessed by the participants and validated through PANAS and the heart rate analyses, support the realistic experience the participants witnessed in the VE. This is shown by the statistical significance related to the user experience and more precisely the high levels of spatial presence, quality of immersion and realism the VR experiment was able to provide. The relation between these factors and the emotional response has been demonstrated in previous research works [24,66] and is in accordance with the results acquired in this study, where we demonstrate this relationship in the context of active shooter incident experiments.

The movement of participants in a VR active shooter scenario is an essential component because of the nature of the scenario under study. Participants, when faced with an active shooter, are recommended to evacuate the building as a first measure and hide as a second measure, both of which necessitate movement. To investigate, the authors looked into the effects of the locomotion technique used on presence, user experience and emotional arousal. The results show that different locomotion techniques (i.e., walk-in-place and controller) used for navigating in the VR simulation can result in different levels of emotional response. The walk-in-place method showed, on average, a larger decrease in the positive emotions and a higher increase in the negative emotions in comparison to the controller-based locomotion technique. This could be because walk-in-place technique is more engaging and promotes a positive walking mechanism as supported by the results, thus enhancing the sense of presence and immersion and boosting the emotional response. Previous studies also demonstrated that the more realistic the locomotion technique employed in a VR experiment the higher the sense of presence will be [82]. Furthermore, scores related to interface awareness were lower in the controller-based technique. This could be attributed to the fact that participants using the controller-based experiment were able to see the joystick floating in the VE which could have affected the realism within the VE.

One limitation of this work is that it focused on a specific population (students) with similar age range (20 to 25 years old). This means that the results of this experiment might be associated with this population. To overcome this drawback, further analysis should be done to take into consideration the variation in the population characteristics as they could affect the emotional and physiological responses of participants. Such analysis can advance our knowledge about how individual factors (e.g., demographics like gender, education level, geographic region, prior experience with emergencies) moderate occupant responses in an

Table 2
Results of independent *t*-test: the effect of locomotion technique on participants' experience.

Class	Walk-in-place average score	Controller average score	t value	p value
Spatial Presence	5.30 ± 1.04	4.70 ± 1.24	2.31	0.02
Interface Awareness	4.79 ± 1.09	4.22 ± 1.35	2.08	0.04
Realism	4.62 ± 1.08	4.63 ± 1.12	−0.03	0.97
Exploration of VE	5.05 ± 1.43	5.15 ± 1.47	−0.27	0.78
Predictability	4.71 ± 1.06	5.10 ± 1.17	−1.67	0.10

active shooter incident. Furthermore, the usability of the locomotion technique might have an effect on the valence and intensity of the emotions: participants who face more usability issues might get more frustrated which could increase their negative emotions. To overcome this issue, we have administered a training session. For future experiments, the duration of the training session could be increased and expanded. However, such training could also take a long time which in return might cause motion sickness and/or fatigue, which is why for this experiment, we chose to balance between the time for training and the issues a longer training might cause. Finally, even a well-trained participant could still have different emotions while using different locomotion techniques due to the equipment itself (e.g., how well the equipment works; how natural the equipment feels, etc.) and as such present different emotional responses when conducting the same experiment using different locomotion techniques. To understand this effect, future research studies could conduct within-subjects experiments to understand if/how the emotional response of the same participant would differ when using different locomotion techniques due to the equipment's strengths and weaknesses.

Finally, beyond what was required by the IRB during review of the experimental plan, we also took an abundance of caution to protect participants from both physical harm and psychological discomfort or triggering that might occur during a VR active shooter incident. Concerning physical pain, we prescreened participants for physical (e.g., heart) conditions that could have been exacerbated by the experiment; in order to safeguard their health, potential human subjects who were at risk were deemed ineligible for the study. While there is inherent risk for psychological discomfort or triggering in a VR experiment of this nature, we chose to reduce this risk by not showing any physical effect of the bullets that hit the virtual occupants (e.g., no blood or torn flesh). While the virtual victims did fall to the ground when hit, we deemed this necessary to successfully simulate an engaging active shooter incident. Research on immersion concurred with our in-depth discussions with law enforcement and security experts: while the active shooter needed to impact (e.g., hit) the virtual occupants in order to be realistic, human users can still be engaged with an immersive experience when visual details like blood and torn flesh are omitted [90].

Indeed, research suggests that a VR experiment does not necessarily have to re-create exactly the real environment to be effective [91]. Just like TV and filmmakers create the feeling of being in the situation without needing a literal reenactment or re-creation, so can designers. A recent review of the literature on fidelity found that, while some argue theoretically for the importance of such "physical" fidelity (i.e., the degree to which the simulation looks real), psychological fidelity (i.e., believability or "human-like" behavior of virtual actors) has been shown to be more important empirically [92]. This suggests that VR experiments can have lower physical fidelity as long as such psychological fidelity is high (e.g., the virtual characters behave realistically). Accordingly, we focused our efforts on simulating realistic behavior of virtual characters over life-like graphics.

6. Conclusions

In this study, we tested the effectiveness of an active shooter VR experiment on emotional and physiological responses to evaluate the realism of the active shooter scenario for research or training. Additionally, we considered different locomotion techniques (i.e., walk-in-place and controller) and explore their impact on users' sense of presence. A VR experiment scenario was established in a school environment, where an active shooter enters the school and commences shooting at people. Participants had the option of running away from the shooter and exiting the building or hiding until the experiment ends. The results demonstrate the VR active shooter experiment induces emotional arousal and increases heart rate of the participants immersed in the virtual environment. The results also support the use of the walk-in-place locomotion technique compared to the controller-based locomotion technique to induce higher sense of presence and immersion during the experiment. The study presents a foundation for future active shooter experiment research in VR as it demonstrates the feasibility of these experiments inducing legitimate emotional response. Future work could investigate the use of VR-based active shooter experiments for planning the response of law enforcement agents and establishing safe evacuation procedures for building occupants, as well as training occupants in case of active shooter incidents.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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